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Changes in Erosion and Runoff due to Replacement of Pasture Land with Sugarcane Crops

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Abstract: The planting of sugarcane crops has expanded in the last decade in the southeast of Brazil, mainly due to its use for biofuel production, such as ethanol. This expansion in the State of São Paulo has occupied land that was previously used for cattle production. The change in land use affects soil and water through changes in ground cover and disturbance associated with farming practices. The objective of the following study was to determine the impact on runoff and erosion resulting from the conversion of pastureland to sugarcane for biofuel production. Erosion plots measuring 100 m^2 were built on a farm in Itirapina-SP, Brazil, on land with a slope gradient of 9% and soil composed of Quartz-sand Neosols (Typic quartzipsaments). The treatments were an 18-year old pasture and a new sugarcane plantation, with three replicates for each. After each rainfall episode, erosion and runoff were monitored during the first and second years after sugarcane was planted. The results show increased runoff and soil loss during the first year, though levels decreased in the second year when the sugarcane residue mulch ground cover increased. In addition, the necessary rainfall characteristics (e.g., intensity, duration) required to produce runoff and soil erosion were identified.

Keywords: sediment; land use; experimental plots; Brazil

1. Introduction

Soil erosion is one of the main problems related to land degradation worldwide, as it causes ecosystem services loss and threatens food security [1,2]. Soil losses increase when the land use changes, either from forests to grasslands, or from grasslands to agricultural crops [3–7]. Some types of croplands may have high soil loss rates [8–14], posing concern about the sustainability of this activity.

More than 1898 million tons of sugarcane were produced around the world in 2013. Brazil is the biggest producer with more than 768 million tons, equivalent to 40% of global production, followed by India and China [15]. Of the almost 9.8 million hectares used for this crop in Brazil, 53% was found within the State of São Paulo, accounting for 56% of national production [16]. From 2007 to 2014, the surface area in the state with sugarcane increased from 4.8 to 6.1 million hectares. This expansion is mainly focused on fields formerly used for grazing bovine cattle for meat, which saw a decrease from 7.6 to 5.7 million hectares in the same period [17].

This change occurred rapidly [18–20] and is mainly due to the use of sugarcane as a raw material in ethanol production (used massively as a biofuel in the growing Brazilian automobile biofuel market) and sugar for internal consumption and for export [19]. Adami, Rudorff, Freitas, Aguiar, Sugawara, and Mello [20] analysed satellite images to calculate that 65% of this change was direct, while 35% corresponded to a change from an intermediate stage to annual crops.

According to Martinelli and Filoso [21], growing sugarcane causes erosion due to the exposure of bare soils that are ploughed deeply when the crop is being established and renewed in 5 or 6-year cycles. This occurs mainly between harvest and the growth of new canes. The soil is compacted by the use of heavy machinery in the planting and harvest processes, decreasing water infiltration and increasing runoff and erosion [22,23]. Eroded sediment causes turbidity in water bodies, transports agrochemicals, and produces sedimentation in rivers and lakes [24].

Some measurements and estimates have been made of soil loss and runoff under the local soil and climate conditions. Most are based on rainfall simulation in small areas [25–27], without considering annual variations [28] or using Water Erosion Prediction Project (WEPP) and Universal Soil Loss Equation (USLE) models on watershed scale [29–31]. There are even fewer local diagnostics for erosion on grassland, with most estimates made using the USLE model [32,33]. In general, the sugarcane erosion estimates are higher than those calculated for grassland due to the different interactions between the soil and the crop.

Since past erosion studies of sugarcane and pasture in the State of São Paulo have used different methodologies and were conducted on different soil types and under different rainfall conditions, the results are not directly comparable. This hinders any real assessment of the impact of substituting pasture for sugarcane on soil erosion and runoff.

The objective of this study was to evaluate the impact on soil loss and runoff resulting from converting pasture to sugarcane plantations on soil composed of Quartz-sand Neosols (Typic quartzipsaments), a soil type that is representative of the eastern region of the State of São Paulo, Brazil.

2. Materials and Methods

2.1. Site Location and Description

The experiment is located on a field with a 9% slope gradient and a north aspect on a farm in the municipality of Itirapina-SP (lat −22.1849, long −47.8530, 790 m above sea level Figure 1). The region has an undulating topography with many fields dedicated to beef cattle production. The local climate is high tropical, classified as Cwa according to the Köppen classification—i.e., a warm climate with dry winters. The hydrological year is from October to September with a rainy season from October to March. Average annual precipitation from 1961 to 1990 was 1548 mm (data from the São Carlos weather station located 20 km from the study site) [34].

Figure 1. Location of the municipality of Itirapina in the State of São Paulo, Brazil.

2.2. Soil Description

The soil consists of Quartz-sand Neosols (Typic quartzipsaments); it has a sandy texture and is representative of the eastern region of the State of São Paulo. In order to determine granulometry, composed disturbed soil samples were collected at depths of 0–14, 30, 60, and 90 cm using the densimeter method. Measurements of water retention, porosity, density, and hydraulic conductivity were taken of three undeformed samples collected at depths of 30, 60, and 90 cm.

2.3. Precipitation Records

Precipitation was recorded in the experimental area using an automatic weather station with 0.2 mm resolution. It was programmed to record precipitation every 10 min. The precipitation measurements began on 13 October 2011 with the installation of the weather station. Precipitation separated by intervals of 6 h were considered as independent events [35].

2.4. Erosion Plots

Erosion plots (measuring 20 × 5 m^2) were built in accordance with the indications of Veiga and Prado [36] on a new sugarcane plantation and on a pastureland. The sugarcane was contour planted on beds. Soil was ploughed with tractor at a depth of 30 cm in four passes, and furrows 20 cm deep were built in contours, spaced 1.5 m apart, after the first precipitation at the start of the rainy season on 27 October 2011. The pasture vegetation used for bovine cattle grazing was *Brachiaria decumbens* planted 20 years ago with heights varying from 5 cm to 30 cm. It was managed considering a 30-day rotation of 50 animals 420 kg each, over 5 hectares for 5 days. Each treatment was set up with three replicates (Figure 2). The spaces between the sugarcane plots were kept bare by manual weeding. The borders of each plot were marked with metal edging following the direction of the slope, with the runoff accumulating in a collector connected to a splitter and a tank storage system.

(**A**) (**B**)

Figure 2. Erosion plots with (**A**) sugarcane and (**B**) pasture for cattle grazing. Photographs taken in February 2012.

After each rainfall event, the solid sediments retained in the runoff collectors (mainly large particles of 0.05–2 mm) were collected with a spatula and stored in labelled plastic bags to be dried and weighed in the laboratory. In the tanks containing the remaining runoff and sediment (mainly fine particles in suspension, <0.05 mm) the volume was measured using a previously established height/volume calibration curve. The water was then vigorously agitated to re-suspend the sediments at the bottom of the tank, and 1 L of the sample was collected in a duly labelled plastic bottle. In the laboratory, the dry weight of the sediments was determined using a digital scale with a precision of 0.01 g, after drying the samples in a heater at 105 °C for 24 h. The laboratory results were then totalled according to the total volume of runoff and the total area of the plots.

The erosion measurements were taken during the first year from sugarcane planting until first harvest (1 November 2011–1 November 2012) and then until 1 November 2013 (first ratoon).

2.5. Statistical Analysis

The mean and standard deviation of runoff and erosion values were calculated for each rainfall event over the three plots for each treatment. In order to identify whether the runoff and sediment production were statistically significantly different between the two treatments (level of significance equal to 0.05) the non-parametric Mann-Whitney U test was performed using the statistics software R (version 3.2.5) (R Foundation for Statistical Computing, Vienna, Austria). The same test was used to identify the differences between years.

3. Results

Particle size analysis indicates that the soil is composed of 85% sand, 12% clay, and 3% silt, and is sandy in texture due to its mainly medium-to-fine grain size (0.10–0.05 mm, Table 1).

Table 1. Particle size distribution of the soil at 30, 60, and 90 cm depth.

Depth (cm)	Sand						Silt (0.05–0.002 mm)	Clay (<0.002 mm)
	Very Coarse (2–1 mm)	Coarse (1–0.5 mm)	Medium (0.5–0.25 mm)	Fine (0.25–0.10 mm)	Very Fine (0.10–0.05 mm)	Total		
	($g \cdot kg^{-1}$)							
0–14	16	22	158	349	333	879	33	88
30	5	31	223	518	87	865	34	101
60	5	32	224	494	90	844	30	126
90	4	31	227	485	90	836	39	125

The surface particle distribution is dominated by fine and very fine sand. However, the soil profile is mainly composed by fine and medium sand. There is almost no silt along the whole soil profile, and clay is scarce on the surface, but appears in higher quantities in deeper layers, evidencing a washed soil. Soil porosity (Table 2) is equilibrated between macro and micro pores, as medium to very fine sand are the dominant grain sizes, increasing porosity with depth. The soil profile has a moderate to rapid hydraulic conductivity, with low water retention between field capacity (−0.33 bar) and wilting point (−15.00 bar).

Table 2. Physical properties of the soil at 30, 60, and 90 cm depth.

Depth (cm)	Soil Water Potential (bar)			Porosity			Bulk Density	Particle Density	Hydraulic Conductivity
	−0.06	−0.33	−15.00	Macro (>0.05 mm)	Micro (<0.05 mm)	Total			
	($cm^3 \cdot cm^{-3}$)						($g \cdot cm^{-3}$)		($mm \cdot h^{-1}$)
30	0.196	0.093	0.087	0.183	0.196	0.379	1.64	2.64	147.31
60	0.207	0.086	0.085	0.216	0.207	0.423	1.53	2.65	117.01
90	0.207	0.089	0.080	0.220	0.207	0.427	1.52	2.65	129.34

3.1. Precipitation

During the first year of the experiment (November 2011–October 2012), there were 121 precipitation events, totalling 1459 mm of rainfall. In the second year (November 2012–October 2013), 131 precipitation events accumulated a total of 1389 mm of rainfall (Figure 3). The values were below the annual average of 1548 mm. Comparing only the rainy periods (October to March), the first year had 76 events (885 mm), while the second year had 89 events (953 mm). Comparing the two rainy seasons with the non-parametric Mann–Whitney test, it was seen that there was no inter-annual difference between the figures for total amount (p = 0.8134), intensity (p = 0.849), or frequency (p = 0.6566). The largest event was 156 mm on 13 January 2013. The longest period without rainfall was 65 days, between 17 July and 20 September 2012.

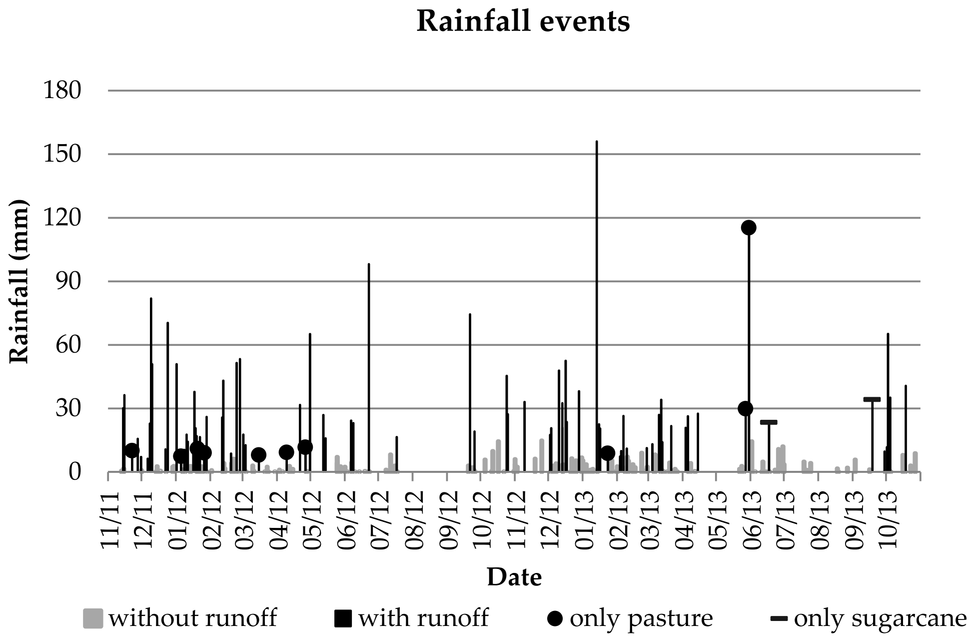

Figure 3. Precipitation records (mm) from November 2011 to November 2013. Grey bars indicate events without runoff; black bars, those with runoff; dot end means events with runoff only in pasture; line end those only in sugarcane.

3.2. Runoff

Not all rainfall events produced runoff (Figure 3), and runoff did not always occur on both treatments. Of the 122 rainfall events (1459 mm) in the first year, only 48 events (totalling 1326 mm) generated runoff from the pasture, and 41 events (1259 mm) from the sugarcane. In the second year, there were 131 rainfall events (1389 mm), of which 34 (1073 mm) produced runoff from the pasture, and 33 events (977 mm) from the sugarcane (Figure 4). The lowest amount of rainfall to produce runoff was 6 mm. All rainfall events with an intensity over 5 mm within 10 min or more than 15 mm in total produced runoff. The first two rainfall events after the dry season in 2012 did not produce runoff (9.8 and 14.4 mm).

Figure 4 presents the average runoff results per event with the precipitation that generated them. The column represents an individual event, with the exception of successive events, when the 6-h interval occurred during the night, making it impossible to collect independent samples. This occurred on 10 December 2011, 11 January, 14 May, 8 June, 3 and 17 December 2012, 4 February, 11 March, 29 May, and 1 October 2013. The events with the most runoff occurred in the following situations: (i) high level of rainfall (total per event) during the rainy season (10 December 2011, 23 January and 28 December 2012, 13 January and 29 May 2013); (ii) frequent rainy periods (16 to 22 January 2012); or (iii) high intensity events (12 February, 21 April, 25 October 2012, 6 February, 12 March, 3 April and 2 October 2013). The runoff values recorded for sugarcane during high intensity events were similar among themselves during the first year (1 to 3 mm) due to the absence of crop mulch in the soil. However, this did not happen during the second year.

The amount of runoff under sugarcane was larger than under pasture in the first year, except for the first two rainfall events, when soil and grass were disturbed due to plot construction. In the second year, the opposite occurred, as sugarcane generated less runoff. This was attributed to the effect of the sugarcane mulch which presented on the soil surface, with the influence of the established cane root system. In the first year, 40.5 mm of runoff from the pasture was recorded (equivalent to 2.8% of the total rainfall), while in the sugarcane, the amount was 56.1 mm (3.8%). In the second year, the pasture generated 56.8 mm of runoff (4.1% of the rainfall) while sugarcane produced only 13.1 mm of runoff (0.9% of the rainfall).

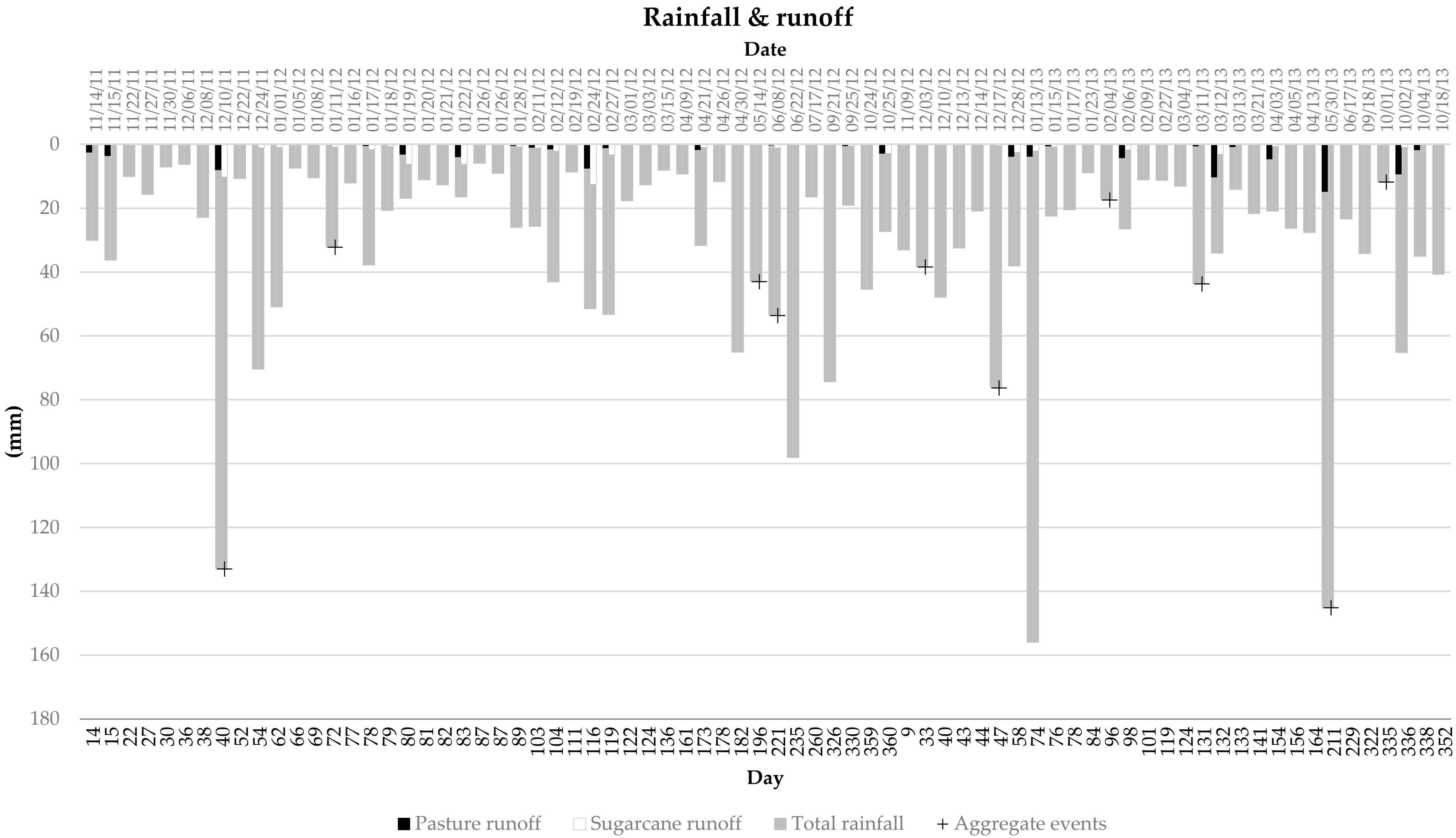

Figure 4. Surface runoff and precipitation per event, for the pasture and sugarcane. Primary *x*-axis indicates days after planting for the first year, and after harvest for the second year. Secondary *x*-axis indicate the dates of runoff events.

The highest runoff (12.5 mm runoff from a rainfall of 51.8 mm, 37.4%, on 23 February 2012) occurred early in the first year, when the sugarcane soil was bare and without residue mulch. In the following year, the sugarcane residue mulch was not uniformly distributed in the field, but was accumulated in every third row, emulating the operation of the harvester. Nevertheless, this accumulation of residue—combined with the sugarcane canopy and roots—decreased the amount of runoff. With the mulch on the soil, the highest total and percentage runoff figure reduced to 3.1 mm and 9.0%, respectively, for the event of 34.4 mm on 12 March 2013. During the same event, the pasture produced its highest runoff percentage for that period (10.3 mm, 37%). This high runoff resulted from the high intensity of this event (10 mm in 10 min), after two consecutive days of rainfall. However, the highest absolute runoff amount (14.9 mm, 26% of the annual total) for the pasture was recorded during the second year (29 May 2013) due to a combination of high rainfall (115.4 mm), long duration (42.5 h), and the event intensity (5.2 mm 10 min^{-1}). Soil compaction from cattle grazing may also have contributed to a larger runoff from pasture than from second-year sugar cane.

Based on these results, it can be said that switching pasture by sugarcane increased runoff by 15.6 mm (1.1% of precipitation) during the first year, but reduced runoff by 43.7 mm (3.1% of precipitation) during the second year. Analysing the treatment results with the Mann–Whitney test shows statistical differences in the first year measurements ($p = 0.008$). The second year did not result in significant differences ($p = 0.2287$). In the second year, sugarcane runoff was reduced, but the pasture results exhibited higher values and higher variability of runoff. Within each treatment, there were significant differences between the first and second year for sugarcane ($p = 0.031$), but not for the pasture ($p = 0.095$).

3.3. Erosion

The erosion results exhibited a declining trend subsequent to plot construction and sugarcane planting. Erosion for the pasture was lower than for the sugarcane, except during the first two events following the soil disturbance by the plot construction process. The amount of pasture sediment then decreased and remained between 0 and 0.05 Mg$\cdot$ $ha^{-1}\cdot$ $event^{-1}$ (Figure 5).

The erosion process for the plots with sugarcane presented three phases during the first year. In the first phase—from planting to January 2012—erosion reached its highest levels with little runoff. The runoff was contained between the contour rows of the sugarcane plants (except in December 2011 under successive events of 82 and 51 mm), where sediments were transported by splash and wash from the uncovered soil close to the collectors.

The second phase (from January to March 2012) occurred when the crops started to grow. An increase in runoff due to crusting and sealing of the soil surface was observed in the field as described in the literature [23,37–39], due to the decreased roughness of the soil [28] and due to sedimentation and break-overs of the contour beds. Sediment was transported along the plots by the concentrated runoff, especially during events with high amounts of rainfall, high intensity, or high frequency, when runoff accumulated along the plot length.

The third phase began in March 2012 and was associated with a reduction in the precipitation frequency leading to reduced erosion, along with the fact that the crop canopy coverage was now developed. The plants protected the soil from the rainfall impact and created a barrier of leaves that reduced runoff. In this phase, the average erosion was 0.01 Mg$\cdot$ ha^{-1} per event, which remained the same until harvest.

In the first year, the crop is referred to as plant-cane, and along the successive years as shoot-cane, with the cane re-growing from the previous roots. Erosion was reduced from 2.58 Mg$\cdot$ $ha^{-1}\cdot$ $year^{-1}$ for plant-cane, to 0.50 Mg$\cdot$ $ha^{-1}\cdot$ $year^{-1}$ for shoot-cane. This reduction is attributed to several factors: the growth of new canopy is faster with shoot-cane than with plant-cane, a perennial root system is already established, and mulch from the previous harvest remains on the soil every three rows, thus considerably reducing erosion.

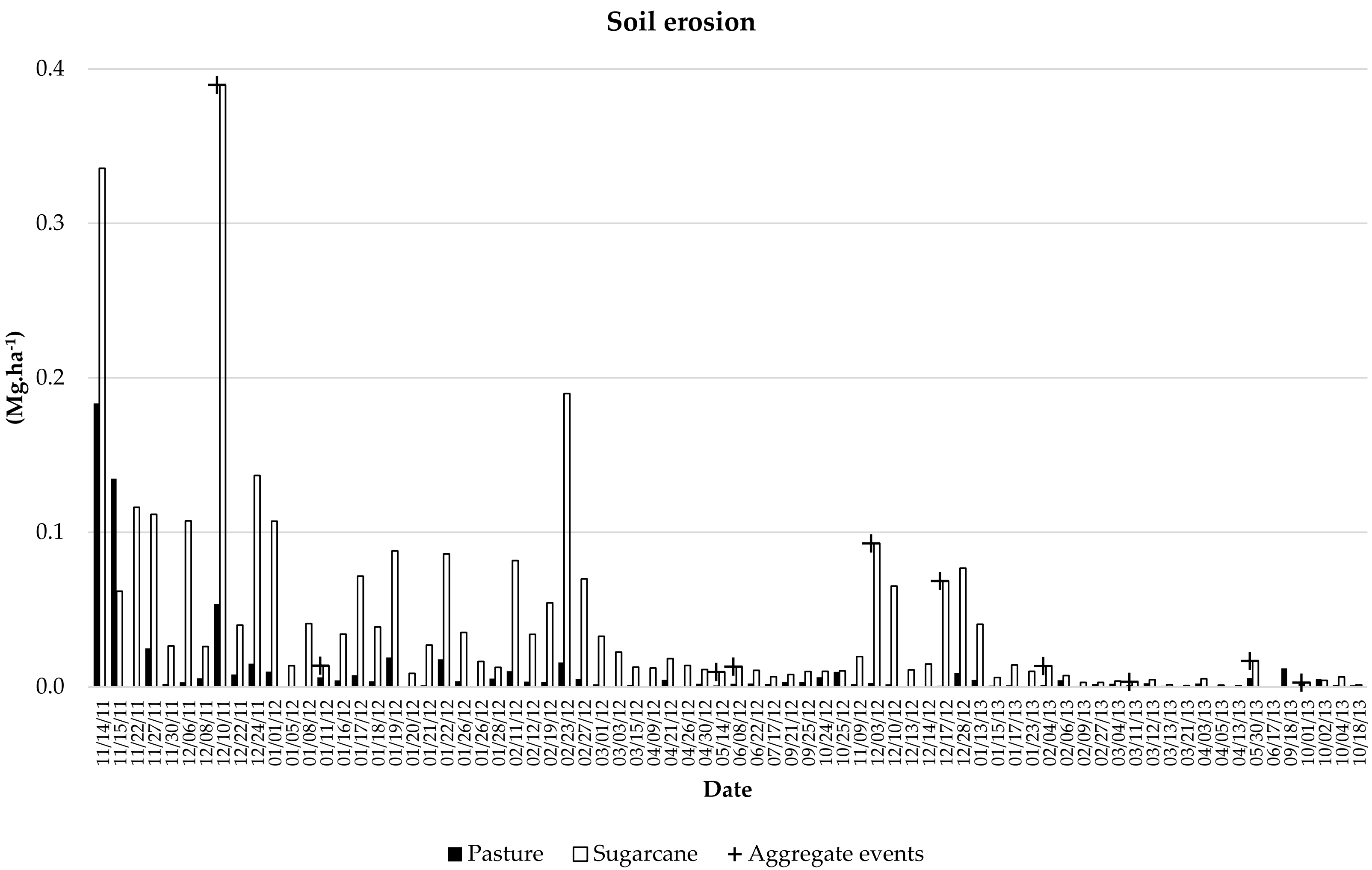

Figure 5. Erosion per event and coverage type.

In the first year, the pasture soil loss was 0.58 Mg· ha^{-1}· year^{-1}, although 0.32 Mg· ha^{-1}· year^{-1} of this occurred during the first events that occurred when the soil was disturbed by the plot construction process. In the second year, erosion decreased to 0.06 Mg· ha^{-1}· year^{-1}. The results show that the substitution of pasture by sugarcane increased the production of sediments by 2.32 Mg· ha^{-1} for plant-cane (first year) and by 0.43 Mg· ha^{-1} for shoot-cane (second year).

In Table 3, the events that generated the highest runoff and soil loss rates, accompanied by information about the precipitation events (rainfall depth, maximum intensity, and duration), are presented. In general, during the first year erosion is more likely to occur, after the construction of the plots on the pasture area (methodological distortion, not representative of the land cover). In the sugarcane plots, the highest values were caused by the soil tillage and its initial condition as fallow.

Table 3. Rainfall characteristics (depth, intensity, duration), which caused the highest runoff and erosion rates. Bold numbers identify the three events with highest runoff or erosion rates by crop. Italic numbers indicate accumulated events.

	Date	PP	Max. Intens.	Duration	∑ PP	Runoff (mm)		Erosion (Mg· ha^{-1})	
		(mm)	(mm 10 min^{-1})	(h)	(mm)	Pasture	Sugarcane	Pasture	Sugarcane
Year 1	14 November 2011	30.2	6.8	13.3	30.2	2.53	0.32	0.18	0.34
	15 November 2011	36.4	5.4	27.2	36.4	3.64	0.31	0.13	0.06
	9 December 2011	82.0	5.4	19.3	133.0	8.03	10.26	0.05	0.39
	10 December 2011	51.0	6.8	4.3					
	22 January 2012	16.6	8.2	1.5	16.6	4.03	6.21	0.02	0.09
	24 February 2012	51.6	10.4	6.5	51.6	7.59	12.54	0.02	0.19
Year 2	12 March 2013	34.2	10.4	8.2	34.2	10.34	3.09	0.00	0.00
	27 May 2013	30.0	6.6	5.3	145.4	14.91	0.11	0.01	0.02
	30 May 2013	115.4	5.2	42.5					
	2 October 2013	65.3	10.8	7.7	65.3	9.38	0.94	0.01	0.00

The Mann–Whitney test gave significant differences between levels of sediment production from the two treatments for the first and the second year ($p < 0.001$). Within each treatment, there were differences between plant-cane and shoot-cane ($p < 0.001$) and a narrow difference between the first and second year for the pasture ($p = 0.049$), due to the higher erosion rates after plot construction.

4. Discussion

The reduction in runoff and erosion for the plots with sugarcane in the second year was likely due to the mulch (leaf residue from the first harvest) that was arranged between every third cane row. This barrier decreased the speed and distance reached by the runoff, favouring sediment deposition. Other studies report the same effect. In Pradópolis (State of São Paulo), a 50% reduction in runoff and an 85% reduction in erosion was recorded for plots measuring 1.0 × 0.5 m^2, with simulated rainfall and with a 50% coverage of mulch between the cane rows when compared with exposed soil [27]. They also found that erosion was minimal when soil residue coverage exceeded 50%, and that there was no statistical difference between 75% and 100% coverage. Sousa, Martins Filho, and Matias [26] evaluated three slope gradients (2.5%, 5%, and 7%) and five levels of mulch coverage (0%, 25%, 50%, 75%, and 100%), reporting that erosion was reduced to the minimum level with coverage of over 50%. Other studies worldwide demonstrated the effectiveness of the use of mulch and planting cover to reduce soil erosion of agricultural ploughed soils [40–42].

In Carpina (State of Pernambuco), Bezerra and Cantalice [37] conducted separate evaluations of the effect of mulch and sugarcane canopy on runoff production and erosion in plots with simulated rainfall, comparing the results with bare soil. They found that the highest level of runoff control was provided by the canopy, as the mulch formed an impermeable layer over the soil. As a result, it decreased infiltration. This phenomenon was not seen in our study, in which the lowest levels of runoff occurred with the presence of mulch. The difference with our own experiment may be attributed to the size of the plots used by the authors (3.0 × 1.0 m^2), where the canopy can have an umbrella-like effect, directing the rainwater outside the plots. With regard to erosion, the authors state that the mulch had a greater protective effect on the soil compared to the canopy, while the combined effect decreased erosion by 99% compared to the bare soil. The roots also helped to reduce soil erosion [43,44].

For a better understanding of soil erosion processes caused by crop changes and their effects in larger areas, it is important to increase the experimental monitoring areas in both spatial and temporal scales [45–48].

5. Conclusions

The substitution of pastureland for sugarcane plantations under the conditions of this field study (sandy soil, 9% slope gradient) increased runoff in the first year, but this then decreases in the second year—attributable to the presence of surface mulch left by the harvester between every third row and soil changes associated with the established cane root system.

Erosion increases by replacing pasture for sugarcane. Discounting the first two events after plot construction, soil loss from pasture lands less than 0.06 to 0.26 $Mg \cdot ha^{-1} \cdot year^{-1}$. Sugarcane has a high level of annual soil loss only during the planting year (2.55 $Mg \cdot ha^{-1}$) due to the perturbation of the soil during the crop establishment and the absence of canopy, mulch, and root system coverage. The level of land erosion with sugarcane decreases in the second year of cropping (0.43 $Mg \cdot ha^{-1}$). Thus, the greatest erosion risk with sugarcane occurs during the establishment year.

The events with the highest levels of runoff occur in the following situations: (i) high rainfall amounts (>15 mm per event); (ii) periods of frequent rainfall; or iii) high intensity events (more than 5 mm 10 min^{-1}). Rainfall events with totals above 6 mm produced runoff.

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